Development of Low-Cost Substrates and Deposition Processes for High-Performance GaAs-Based Thin-Film Solar Cells

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ABSTRACT

We present results for the first phase of an effort to develop large-grain (>1-mm), highly-oriented, 5-micron thick Ge films on fused silica and alumina ceramics. We use a water-vapor mediated, close-spaced vapor transport (CSVT) process to deposit Ge, followed by a recrystallization step. These structures are intended for use as Ge (coated) surrogate substrates for epitaxial growth of high-performance GaAs/InGaP solar cells.

1. Introduction

GaAs-based solar cells have the highest demonstrated efficiencies. For example, InGaP/GaAs/Ge cells developed for space power have conversion efficiencies in the neighborhood of 30%. (References and more detail for the solar cell results cited in this paper can be found at www.pv.unsw.edu.au/eff/.) The typical GaAs-based space solar cell is comprised of a relatively sophisticated epitaxial structure grown by metalorganic chemical vapor deposition on a germanium substrate wafer. These types of cells may be viable for some types of concentrator systems, but are too costly for fixed array terrestrial systems. However, low-cost versions of high-performance GaAs solar cells have been investigated, yielding some significant results. For instance, GaAs-on-silicon solar cells with efficiences greater than 20% have been reported, despite the relatively large lattice and thermal expansion mismatch between GaAs and silicon. Further, an 18% efficient GaAs solar cell grown by MOCVD on an optical-grade polycrystalline Ge wafer with ~1-mm grain size has been demonstrated by an RTI group.

It is natural to ask whether the high-performance of such GaAs-based solar cells can be translated into a low-cost, polycrystalline thin-film configuration. Considerable efforts were directed in this area in the late 1970s and early 1980s. The results were—for the most part— disappointing: the solar cell performance was severely limited by small grain size (10 to 100 microns), electrically active grain boundaries, and shunting problems. No satisfactory low-cost substrate compatible with high efficiency performance was identified. Simple and effective surface passivation techniques, as an alternative to epitaxial AlGaAs "window", layers were lacking.

Almost two decades later, thin-film poly GaAs cells merit revisiting, especially in view of the GaAs-on-silicon and GaAs-on-polycrystalline Ge results mentioned already, the continued record-breaking results in single-crystal GaAs-based solar cells, and the potential of new methods for surface and grain boundary passivation. Also, new concepts and processes developed for thin-film poly- and amorphous-silicon, and II-VI compound solar cells provide a versatile technology base to exploit for GaAs cells.

2. Technical Approach

The basic idea is to produce a low-cost, polycrystalline germanium thin-film structure which is functionally equivalent to the optical-grade polycrystalline Ge wafers used in the RTI work cited above. The second phase is to develop low-cost epitaxy methods for GaAs and InGaP using the surrogate Ge-coated substrates developed in the initial phase. Based on the RTI work, grain sizes in excess of 1-mm are needed. An equally important criterion is to select a substrate that has a close thermal expansion match to Ge and GaAs (which have similar thermal expansions). Other considerations for the substrate include low-cost, chemical inertness, a minimum smoothness, and good adhesion of deposited Ge films. A conducting substrate is often considered a necessary feature in order to make back contact. However, insulating substrates facilitate advanced design concepts based on monolithic series interconnection to achieve high-voltage minimodules.

We are depositing the Ge and GaAs films using a simple atmospheric-pressure Close-Spaced Vapor Transport (CSVT) process, which is shown schematically in FIGURE **1**. The deposition is based on a reversible reaction using water vapor (2000 ppm_v H_2O in a 15%H_2/85%N_2 carrier gas flowing at 20 ml/min) as a transport agent. The solid Ge or GaAs source and substrate are separated by a 1-mm gap and are heated individually by infrared lamps such that the source is held approx. 50 °C hotter than the substrate. The relevant transport reactions are:

$$2 \cdot \mathrm{GaAs\ (s)} + \mathrm{H_2O\ (v)} \underset{800\ ^\circ\mathrm{C}}{\overset{850\ ^\circ\mathrm{C}}{\rightleftharpoons}} \mathrm{Ga_2O\ (v)} + \mathrm{H_2}(g) + \tfrac{1}{2}\mathrm{As_4\ (v)}$$

$$\mathrm{Ge(s)} + \mathrm{H_2O\ (v)} \underset{800\ ^\circ\mathrm{C}}{\overset{850\ ^\circ\mathrm{C}}{\rightleftharpoons}} \mathrm{GeO\ (v)} + \mathrm{H_2}(g)$$

At the source, the GaAs or Ge is oxidized to form volatile components which diffuse to the substrate and react to form a GaAs or Ge film. Deposition rates of 1 micron/min are typical. The Ge film is then recrystallized in a post-growth annealing step (see below). Ge and GaAs CSVT using iodine as the transport agent is also under development.

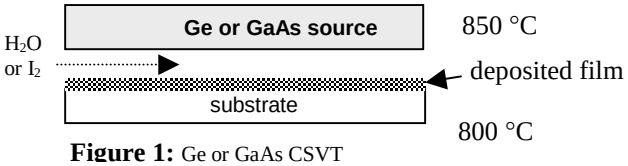

Figure 1: Ge or GaAs CSVT

To study various effects, we are utilizing a variety of substrates including: single-crystal silicon, germanium, and GaAs of (100), (110), and (111) orientation, various polycrystalline silicon (Wacker Silso™, silicon-on-ceramic, Silicon-Film™), polycrystalline Ge and GaAs, silicon coated with a thermal oxide, fused silica, sintered alumina, SiC, mullite; and molybdenum, tantalum, and stainless steel sheet. The substrates are coated with a 5-micron thick film of Ge deposited by the CSVT process described above and then capped with a 0.5-micron thick aluminum layer deposited by electron-beam evaporation. The Ge-coated substrate is then subjected to a thermal treatment in purified hydrogen with temperatures in the 800 to 950 °C range for 10 to 30 minutes. The Al cap prevents agglomeration of the Ge film during a post-deposition annealing/ recrystallization step. The Al cap also appears to promote large-grain, oriented recrystallization of the deposited Ge film by a mechanism that is not yet certain.

3. Results and Achievements

FIGURE **2** shows the as-deposited Ge film, with grain sizes on the order of 10 microns; no highly preferred orientation is evident. The samples are then recrystallized (FIGURES **3** and **4**) showing a much enhanced grain size (several millimeters) and a dominant (111) texture (FIGURE **5**). Best results have been achieved on polished fused silica, although unfortunately, this substrate is not closely thermal expansion matched to Ge and GaAs. Alumina substrates also exhibit large-grain, oriented growth, but not as dramatic as with the fused silica substrates. We are continuing efforts on alumina substrates, particularly with respect to optimizing the surface finish in relation to its effect on recrystallization.

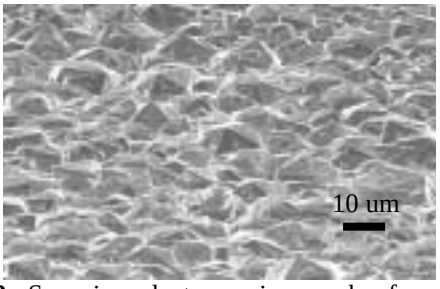

FIGURE 2: Scanning electron micrograph of as-deposited Ge film on alumina ceramic substrate.

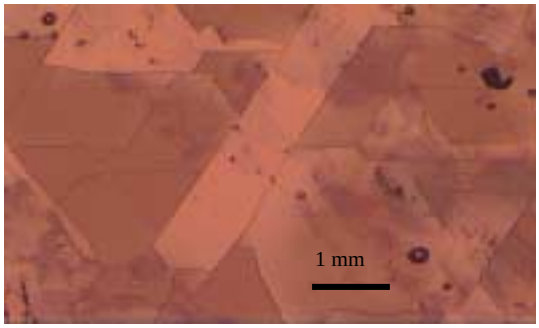

FIGURE 3: Top-view photomicrograph of recrystallized 5-micron thick Ge film on fused silica substrate.

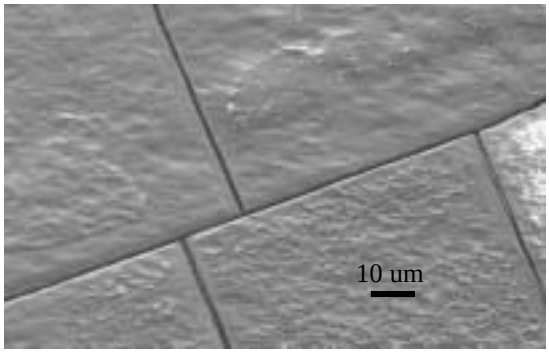

FIGURE 4: Scanning electron micrograph of recrystallized Ge film on fused silica substrate.

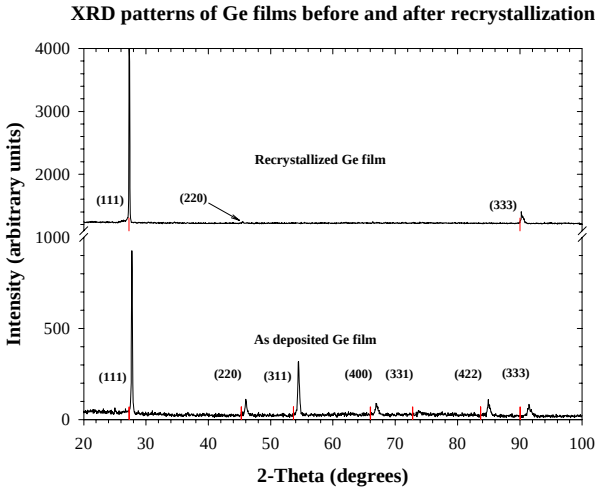

FIGURE 5: X-ray diffraction of Ge films before and after recrystallization.

4. Conclusion.

Large-grain, highly-oriented films of Ge on several substrates (fused silica and alumina) are feasible using simple processing techniques. We are currently seeking to optimize the process for alumina substrates, reduce the Ge layer thickness to lower materials costs, and assess the structures as substrates for GaAs epitaxy.

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